

Multidomain analysis and wavefield separation of cross-well seismic data

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ABSTRACT

While cross-well traveltime tomography can be used to image the subsurface between well pairs, the use of cross-well reflections is necessary to image at or below the base of wells, where the reservoir unit is often located. One approach to imaging cross-well reflections is to treat each cross-well gather as an offset VSP and perform wavefield separation of direct and reflected arrivals prior to stacking or migration. Wavefield separation of direct and reflected arrivals in VSP is accomplished by separating the total wavefield into up and downgoing components. Since reflectors can exist both above and below the borehole wavefield,

separation of cross-well data into up- and downgoing components does not achieve separation of direct and reflected arrivals. In our technique, we use moveout filters applied in the domain of common vertical source/receiver offset to extract reflected arrivals from the complex total wavefield of a cross-well seismic data set. The multiple domains available for filtering and analysis make cross-well data more akin to multi-fold surface seismic data, which can also be filtered in multiple domains, rather than typical VSP data, where there is only one domain (common source) in which to filter. Wavefield separation of cross-well data is shown to be particularly effective against multiples when moveout filters are applied in common-offset space.

INTRODUCTION

Cross-well seismic tomography is a popular method of monitoring enhanced oil recovery processes such as steam flooding (Macrides et al., 1988; Justice et al., 1989). In cross-well traveltime tomography, a seismic source is activated in one well, traces are recorded with receivers located in nearby well(s), and the direct arrival traveltimes are picked and used to tomographically reconstruct the subsurface velocity function between the two wells. Recently, investigators have been attempting to use the reflection arrivals present in cross-well data to enhance and extend the imaged region between the two wells (Stewart and Marchisio, 1991; Lazaratos et al., 1991). The extension from cross-well tomography to cross-well reflection images is analogous to the development of vertical seismic profiling (VSP), which grew out of the checkshot survey (Hardage, 1985). Important reservoir zones at the base of the wells can be illuminated by reflection. In cross-well tomography, few

raypaths traverse the region near the well base and therefore reconstructed images in these regions may be lower quality.

To extract and image "upgoing" reflected arrivals recorded in VSP data, a variety of signal processing techniques are used. A standard VSP processing sequence consists of wavefield separation, deconvolution, and mapping (Balch and Lee, 1984; Hardage, 1985). In wavefield separation, the moveout differences between the upgoing reflected arrivals and the downgoing transmission arrivals are used to dissect the total wavefield into the upgoing and downgoing components. Wavefield separation is generally required to produce a coherent reflection image because VSP data typically contain little stacking fold. Multiples are attenuated through deconvolution of the upgoing wavefield using an operator derived from the downgoing wavefield (Anstey, 1980). The wavefield-separated, deconvolved upgoing reflections are mapped from the domain of time versus depth to the domain of two-way time (or depth) versus borehole offset using a

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VSP-CDP transform (Wyatt and Wyatt, 1981) or a limited aperture migration (Van der Poel and Cassel, 1989).

In a recent study, Lazaratos (1993) showed that the quality of a cross-well reflection image could be improved by performing velocity analysis prior to stacking or migration of different gathers. The velocity analysis was improved by first performing wavefield separation and isolating the desired reflected arrivals from coherent interference. Therefore, wavefield separation may become an important component in producing a coherent stacked or migrated cross-well reflection image.

A cross-well data set can be thought of as a series of "offset" VSPs where source elevation varies and horizontal offset remains constant. VSP processing techniques can be used to extract and image cross-well reflection arrivals from each offset independently, stacking the data from different source elevations after mapping. However, cross-well data have several characteristics that are not present in a conventional VSP. The presence of reflecting layers below and above the source and receiver, as well as the wide reflection angles (generally greater than 45 degrees), create new wave phenomena that require modifications to standard VSP wavefield separation techniques.

Complex cross-well wavefields require wavefield separation techniques that are more discriminatory than VSP wavefield separation techniques. For example, since each arrival type can be either up- or downgoing depending on whether the source is above or below the receiver, VSP wavefield separation techniques that split the total wavefield

into up- and downgoing components will not separate the cross-well wavefield into direct and reflected arrivals.

In this paper, we characterize the moveouts of selected cross-well arrivals in different sorting domains and we describe a method by which cross-well data can be wavefield separated to extract reflection arrivals. The method uses moveout-based filtering in common *offset* space, where *offset* refers to the vertical separation of source and receiver, to extract primary reflections from the complex total wavefield.

CROSS-WELL SHOOTING GEOMETRY AND STACKING CHART

Figure 1 shows a typical shooting geometry for cross-well surveys. A receiver string of geophones, accelerometers or hydrophones is lowered into one well and a seismic source is lowered into another. Common source or receiver "fans" of data are recorded over a range of wireline depths. These fans typically cover ray angles, defined as the angle that a straight line between a source/receiver pair forms with the vertical, ranging from ± 45 degrees to 90 degrees (Iverson, 1988). With this geometry a cross-well data set can be considered to have a stacking chart like the one in Figure 2 (Stewart, 1991). As shown in Figure 2 the cross-well data set can be sorted into (1) common source depth, (2) common receiver depth, (3) common midpoint (also called common middepth (Stewart, 1991), or (4) common offset gathers. These different gather types are analogous to the common shot, receiver, offset, and midpoint gathers of surface reflection geometries except that wireline

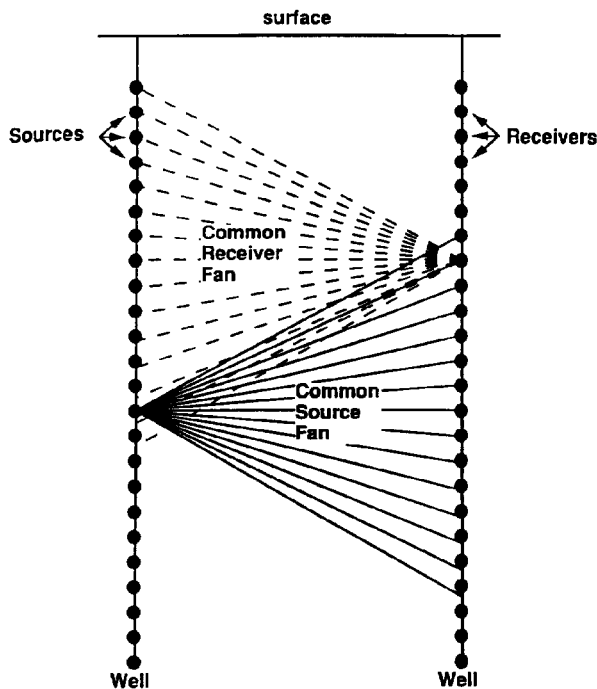


FIG. 1. Typical cross-well seismic survey geometry. Sources are in one well, receivers in the other. The solid and dashed lines show idealized direct raypaths for common source and common receiver gathers.

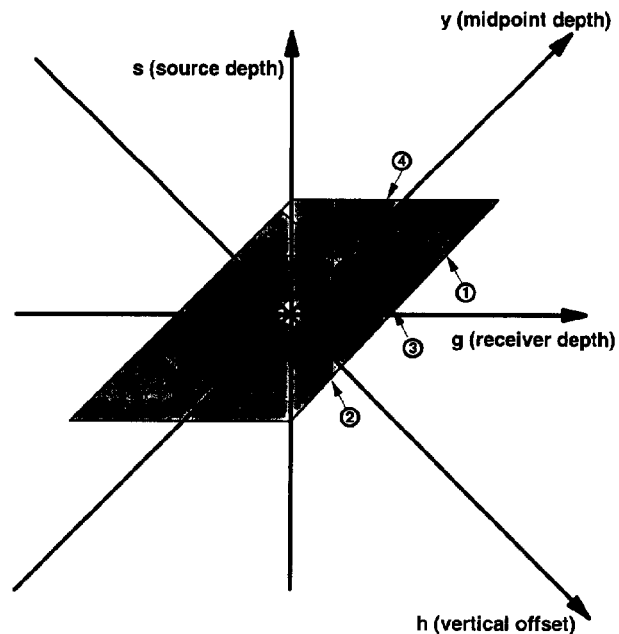


FIG. 2. Cross-well survey stacking chart. (1) is a common shot gather, (2) is a common-receiver gather, (3) is a common-midpoint gather, and (4) is a common-offset gather. The independent variable is depth rather than horizontal position associated with surface seismic stacking charts. [Modified from Yilmaz (1987)]

depth is the relevant independent variable rather than lateral position at the earth's surface. Figure 3 illustrates the raypaths taken by direct arrivals and upgoing reflections in the different domains. Using the terminology of Claerbout (1985), the vertical offset h is defined as $g - s$, where g is the geophone depth and s is the source depth. The midpoint y is defined as $(g + s)/2$.

Although the analogy to surface seismic stacking charts is a useful one, reflections have very different representations in the cross-well geometry than they do in the surface seismic geometry. For example, in a region of zero dip, the surface seismic common midpoint is also a common-reflection point (CRP). In the cross-well geometry, the common-midpoint (CMP) gathers contain reflections from many points between the source and receiver wells. A cross-well CMP gather does not correspond to a common reflection point. In fact, as shown in Figure 3, none of the four gathers are cross-well common-reflection points.

In a homogeneous earth, the direct arrival moveout M_d between two adjacent traces can be written as:

$$M_d = (s - g)(\Delta s/\Delta z - \Delta g/\Delta z)/[(s - g)^2 + x^2]^{1/2}\alpha, \quad (1)$$

where α is the velocity, $\Delta s/\Delta z$ and $\Delta g/\Delta z$ are the source and receiver wellbore sampling intervals, and x is the well-to-well separation (with the wells assumed to be vertical). For common receiver gathers, $\Delta s/\Delta z$ is nonzero but $\Delta g/\Delta z$ is zero. For common source gathers, $\Delta g/\Delta z$ is nonzero but

$\Delta s/\Delta z$ is zero. For common offset gathers acquired with equal source and receiver sampling intervals, $\Delta s/\Delta z = \Delta g/\Delta z$, and the moveout of the direct arrival is zero provided the velocity is constant. In heterogeneous media, common-offset space provides a domain in which the variation of velocity with depth (based on changes in the direct arrival traveltime) can be characterized. Harris (1988) used zero offset data to characterize formation velocity at a horizontally stratified site. In common-midpoint space acquired with equal sampling intervals, $\Delta s/\Delta z = -\Delta g/\Delta z$, and the direct-arrival moveout is twice the moveout of the direct arrival in common source or receiver space.

The moveout of an arrival coming from a horizontal reflector in a homogeneous earth M_r can be written as:

$$M_r = (s + g - 2z_r) \times (\Delta s/\Delta z + \Delta g/\Delta z)/[(s + g - 2z_r)^2 + x^2]^{1/2}\alpha, \quad (2)$$

where z_r is the reflector depth. For upgoing reflections, s and g are less than z_r , and for downgoing reflections, s and g are both greater than z_r . In common source or receiver space, the reflector moveout is hyperbolic, and the apex of the hyperbola is approached as the source (or receiver) approaches the reflecting interface. In common-offset space, a reflection arrival has roughly twice the moveout that it has in common source or receiver space; whereas in common midpoint space, the moveout of the reflection is zero provided source and receiver wellbore sampling intervals are equal.

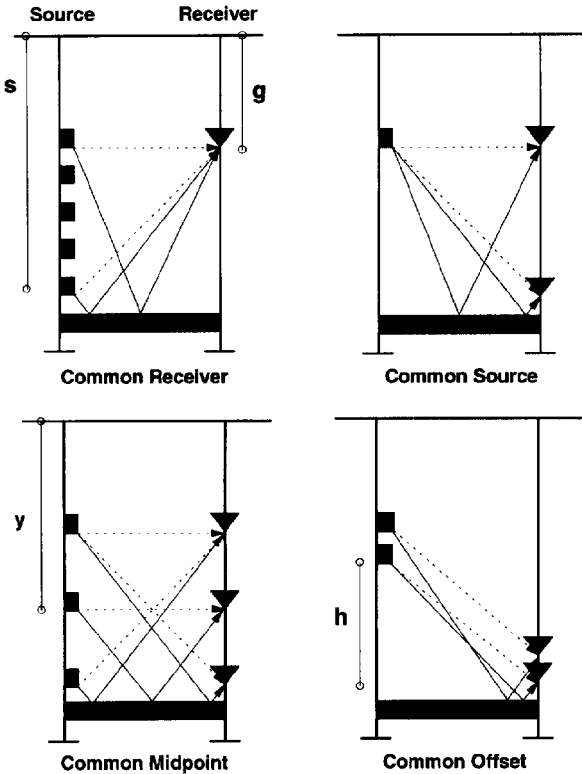


FIG. 3. Raypath diagrams of direct and upgoing reflections in the different gather spaces, s , g , y , and h are functions of depth.

SYNTHETIC EXAMPLE OF CROSS-WELL WAVEFIELD SEPARATION

To illustrate the moveouts of some of the principal cross-well arrivals in the different gather domains and evaluate two different wavefield separation techniques, we created a synthetic data set from the simple earth model shown in Figure 4. Sources were positioned every 2 ft (.61 m) between 312 ft (95 m) and 406 ft (124 m), and receivers were located every 2 ft (.61 m) between 300 (95 m) and 498 ft (152 m). Initially, an acoustic synthetic data set including all multiples

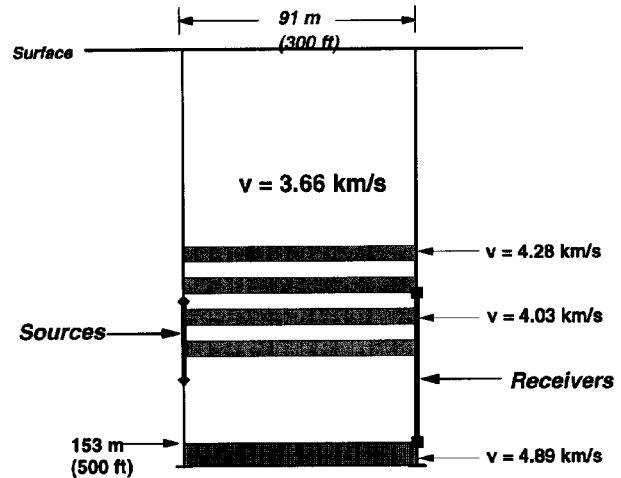


FIG. 4. Geometry used to create synthetic cross-well data.

was generated assuming an omnidirectional P -wave source radiation pattern with a 1250-Hz Ricker wavelet and a receiver recording vertical displacement. The data were generated using Sierra Geophysics' viscoelastic modeling algorithm, VESPA (Apsel, 1979). It should be noted that this modeling algorithm does not include boreholes, and therefore tube waves, which can be an energetic component of cross-well wavefields, were not included.

Direct and reflected arrivals

Figure 5 shows an example of a common-source gather (CSG), a common-receiver gather (CRG), and a common-offset gather (COG). The data are displayed after normalizing each trace to the maximum amplitude in the 0 to 50 ms time window. In Figure 5 we have labeled the P -wave direct arrival as well as upgoing and downgoing primary P -wave reflections. Linear moveout head-wave arrivals crossing over the direct arrival can also be seen. The raypaths taken by the direct and reflected arrivals are shown in Figure 6. In the common-source domain (and likewise in common-receiver space), the direct transmission arrival has noticeable moveout with depth, with a minimum traveltime roughly corresponding to zero vertical offset between source and receiver (i.e., the source and receiver at the same depth). The upgoing and downgoing reflections also have noticeable moveout with depth. As predicted by equation (1), the direct-arrival path length and traveltime are roughly constant in the common-offset gather. By contrast, the upgoing and downgoing reflections have moveouts in common-offset space that are roughly twice the moveout of common source or receiver space. From Figure 6 it can also be observed that the wavefield becomes less "complicated" as offset increases. This is a characteristic sometimes observed in

cross-well seismic data recorded in horizontally stratified media. The Zoeppritz equations for plane wave reflection and transmission at interfaces (Waters, 1978) predict that as the incidence angle increases, more head waves and post-critical reflections will be generated. These arrivals contain significant energy and can strongly affect the direct-arrival signal. In some instances, the direct-arrival signal may not be identifiable at the near offsets.

For the purposes of wavefield separation, it is important to note that when the distance between source or receiver and the reflecting interface is large, the moveout of the reflected arrival becomes similar to the moveout of the direct arrival. This can also be seen from inspection of equations (1) and (2). Thus, moveout-based wavefield separation techniques applied only in one domain, common source, or common receiver will have difficulty in separating reflection arrivals from the direct arrivals for some trace depths.

The problem of cross-well direct- and reflected-arrival wavefield separation was noted by Pratt and Goultz (1991), who showed that common offset was a more optimal domain for separating direct and reflected wavefields than common-source or common-receiver space. When the data are sorted to the domain of vertical offset, the direct arrival can be moveout distinguished from both the upgoing and downgoing reflected arrivals for all depths. Rather than separating the arrivals based on incoming direction (i.e., upgoing versus downgoing) the offset domain distinguishes between different acoustic arrivals on the basis of *path length*. The raypath length of the direct arrival is roughly *constant* in a common vertical-offset gather, and therefore traveltime changes are related to vertical velocity variations rather than path length variations. This phenomena can also be observed in equation (1), where the direct arrival moveout M_d is zero

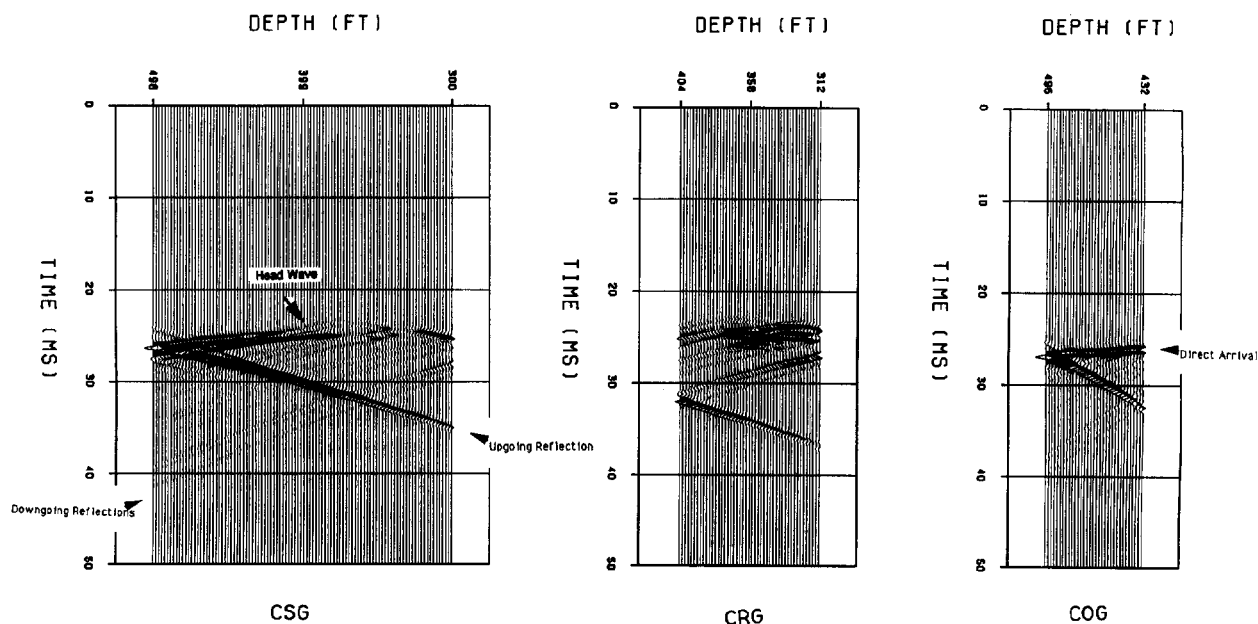


Fig. 5. Acoustic synthetic cross-well gathers. CSG = common-source gather, CRG = common-receiver gather, and COG = common-offset gather.

provided the source and receiver spacings are equal. By contrast, as shown by equation (2) and Figure 5, the primary downgoing and upgoing reflected arrivals in common vertical-offset gathers have moveout magnitudes that are roughly *twice* the moveout of their common source or receiver counterparts. In common source or receiver space, one leg of the reflected travel path changes while the other leg remains approximately constant. In common offset space, both legs of the reflected path decrease as the source and receiver approach the reflecting horizon (see Figure 6b).

Multiples

As stated previously, one of the unique aspects of cross-well data is the ability to record downgoing as well as upgoing reflections. With two image perspectives on each interface (the interfaces intersected by the well are viewed from above and below), more quantitative impedance estimates should be possible. An attendant problem for cross-well wavefield separation is the presence of many interfaces

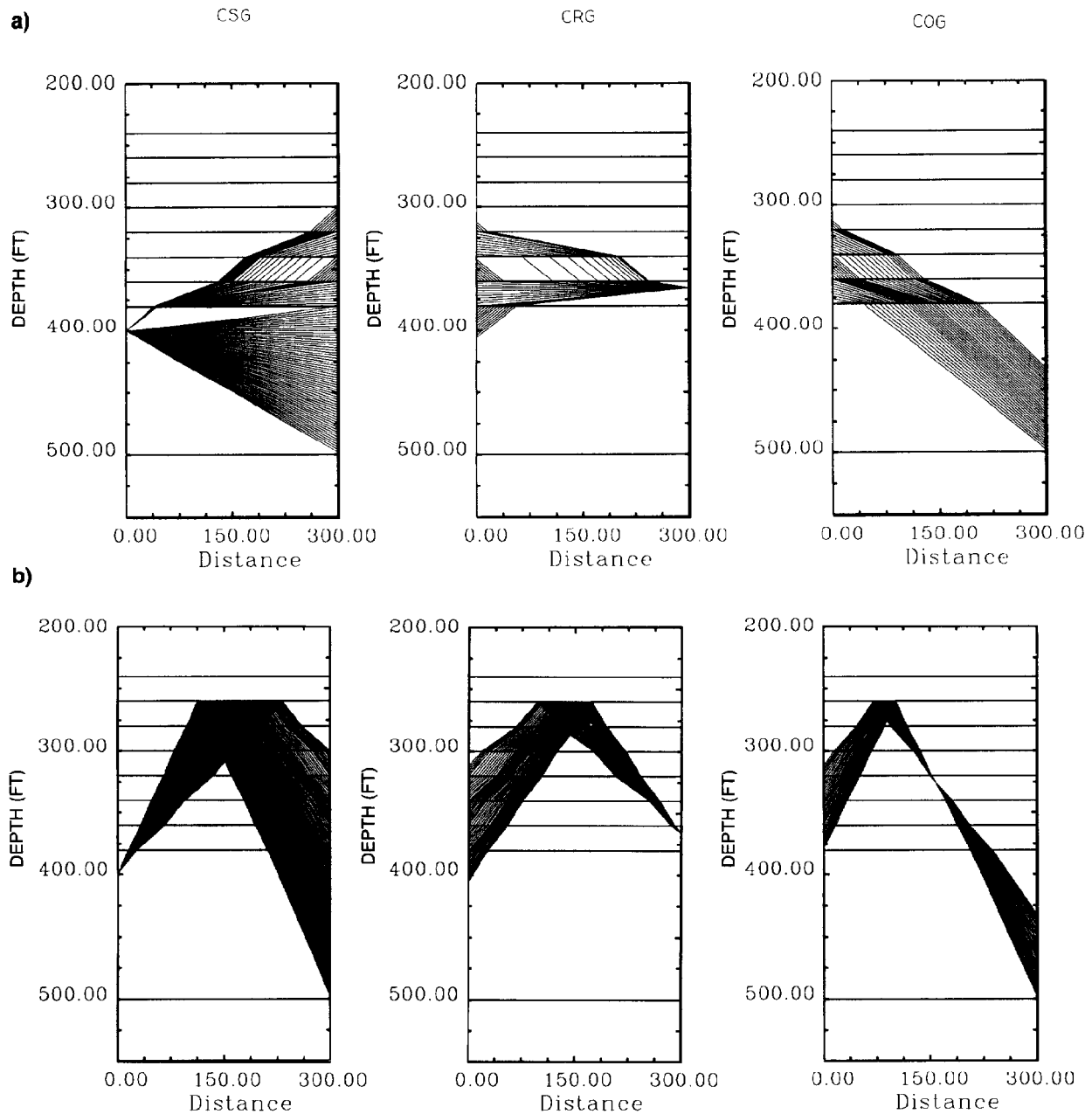


FIG. 6. Raypaths taken by different arrivals for the gathers shown in Figure 5; (a) direct arrivals (b) downgoing reflection (c) upgoing reflection. The source well is on the left and the receiver well is on the right.

below and above the source and receiver that can generate multiples.

Figure 7 is the acoustic synthetic of Figure 5 displayed with a 15-ms AGC to enhance the weaker multiples. The weaker multiples can be distinguished from primary reflections because they terminate against a primary reflection, whereas primary reflections terminate against the direct arrival. A raypath for one of these multiples is depicted in Figure 8. Like primary reflections, multiples can be grouped into downgoing and upgoing types based on the raypath leg connecting the reflecting interface to the variable parameter (e.g., source or receiver). The moveout of this type of multiple M_m can be expressed (for a homogeneous earth) as:

$$M_m = \{s - g + 2(z_r - z_m)\} \{ \Delta s / \Delta z - \Delta g / \Delta z \} / [\{s - g + 2(z_r - z_m)\}^2 + x^2]^{1/2}, \quad (3)$$

where z_m is the depth of the multiple-generating interface. Note that the depths z_r and z_m can be interchanged. In other words, the multiple can be viewed as coming from z_r and the primary can be viewed as coming from z_m . In a common source or receiver gather, upgoing multiples have a moveout that is similar to other upgoing arrivals (direct and primary reflected arrivals) and downgoing multiples have a moveout that is similar to other downgoing arrivals. Consequently, these multiples cannot be distinguished from primary reflections on the basis of moveout in common source or receiver space.

In conventional VSP, some upgoing multiples (those produced above the reflecting horizon) are attenuated by deconvolving the upgoing wavefield with an operator derived from the downgoing wavefield (Hardage, 1985). The critical assumption made in this deconvolution process is that multiples in the upgoing wavefield have the same amplitude and timing relationships to the upgoing primary as multiples in the downgoing wavefield have to the downgoing direct

arrival. This is strictly true only for vertical incidence VSP data in a horizontally stratified earth (Hardage, 1985). The assumption is no longer valid for offset VSP or cross-well data, and different techniques may be necessary to separate primary reflections from multiples.

One way to separate multiples from primary reflections is to perform wavefield separation in common-offset space rather than common source or receiver space. Note that in common-offset space the multiples have nearly zero moveout, like the direct arrival. This can also be seen by inspection of equation (3). As mentioned previously, moveout-based wavefield separation in common-offset space distinguishes between acoustic arrivals that have relatively constant path lengths and arrivals whose path lengths either increase or decrease. In the former category are direct arrivals and two bounce (and other even order bounce) multiples. In the latter category are primary reflections (with one bounce) and odd-bounce multiples.

To demonstrate the improved prestack reflection image quality obtained when cross-well data are wavefield separated in common-offset space, the acoustic model data (shown in Figure 5) were processed using two different processing flows. The first used conventional VSP wavefield separation applied in common-source space; the second used wavefield separation applied in common-offset space. Wavefield separation in common source space consisted of:

- 1) Sorting the data to common-source space.
- 2) Aligning the data and normalizing each trace to the rms direct-arrival amplitude.
- 3) Removing the direct arrival with a 21-trace mix followed by subtraction of the mixed data from the aligned and normalized output of the previous step. Twenty-one traces, representing 42 ft (13 m), were judged to span the longest wavelength of the downgoing reflection in common-source space (with the direct arrival flattened).

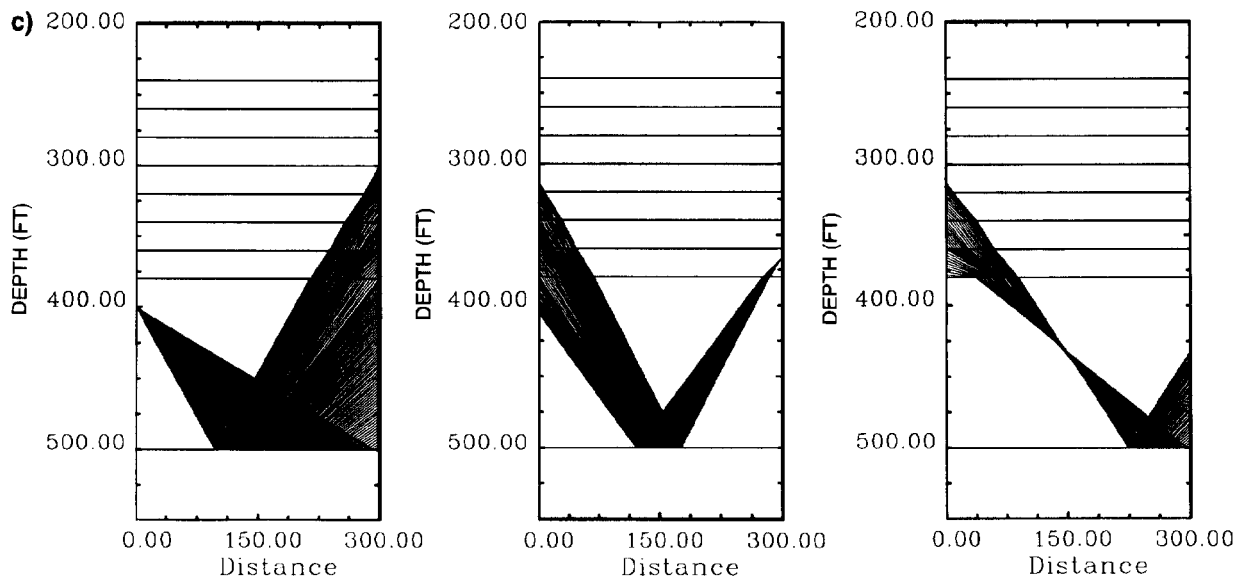


FIG. 6. continued

- 4) Separating the upgoing from the downgoing arrivals by passing only those arrivals with apparent velocities between 7000 ft/s (2100 m/s) and 50 000 ft/s (15 000 m/s) using a standard f - k fan filter. The velocity passbands were estimated from the f - k spectrum as the -6 dB points of the downgoing reflection energy in the $+k$ quadrant.

Wavefield separation in common offset space consisted of:

- 1) Sorting to common offset (i.e. grouping together traces with equal source/receiver separation)
- 2) Aligning the data and normalizing each trace to the rms direct arrival amplitude.

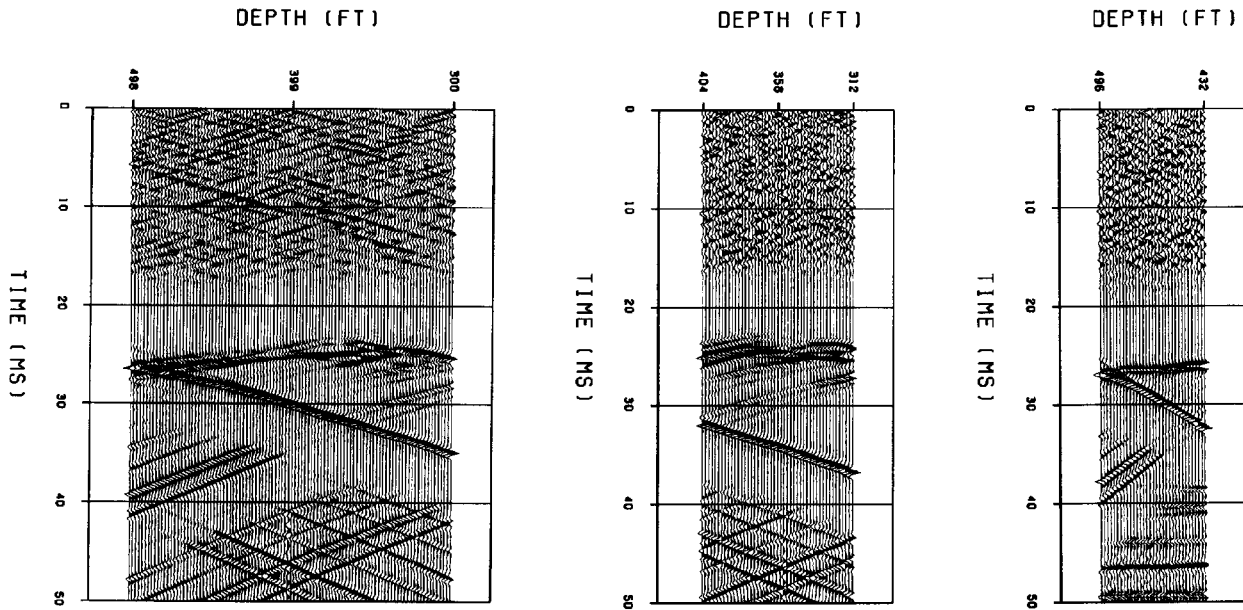


FIG. 7. Data of Figure 5 displayed with a 15 ms AGC to enhance weaker multiples.

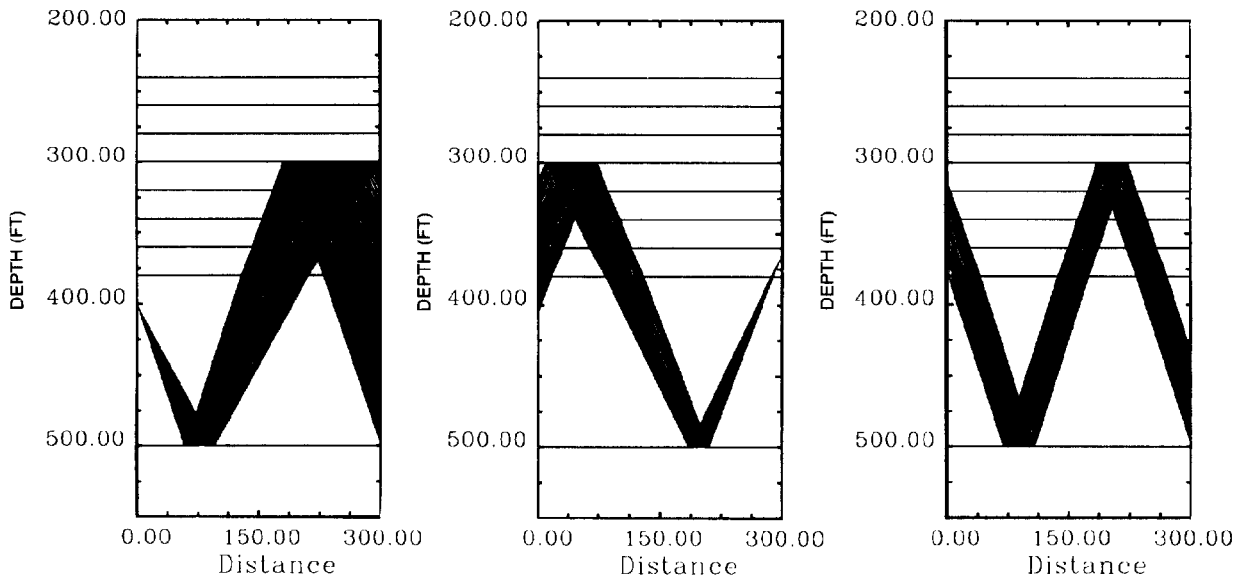


FIG. 8. Raypaths taken by a cross-well multiple arrival.

- 3) Removing the direct arrival with an 11-trace mix. Eleven traces, or 22 ft (7 m), were judged to span the longest wavelength of the downgoing reflections in common-offset space (with the direct arrival aligned).
- 4) Separating downgoing from upgoing reflections by passing arrivals between velocity cutoffs of 7000 ft/s (2100 m/s) and 30 000 ft/s (9200 m/s).

Figure 9 compares the mapped output of the two processing flows with the mapped primary reflection wavefield created by a geometric ray-tracing algorithm. A single common-source gather at a source depth of 386 ft (120 m) was used as input to the mapping for each of the reflection images in Figure 9. The downgoing reflections were mapped from the time and depth variables of cross-well acquisition space to image space with a VSP-CDP transformation (Wyatt and Wyatt, 1981) modified for the cross-well geometry. The velocity function shown in Figure 4 was used to map the reflection wavefield. The data in Figure 9 are displayed in true depth (roughly a 1:1 scale) with a 30-ft (9.16-m) AGC applied. The data near the bottom of the section appear to be lower frequency because of the data stretch, similar to normal moveout (NMO) stretch, in the mapping process (Lazaratos et al., 1991). Note in Figure 9 that there is greater continuity of the primary reflections when the common offset wavefield separation is used. Also note that the horizontal arrivals above 210 ft (60 m) in Figure 9c are artifacts produced by the multiples. These artifacts are substantially attenuated in the offset-processed section (Figure 9a).

The results shown in Figure 9 are somewhat deceiving because the section processed in common offset used the entire data set for wavefield separation whereas the common

source wavefield separation was done with a single source gather. Wavefield separation in both common source *and* common receiver or stacking of multiple source gathers may have produced results comparable to the common-offset processed image. However, the former process requires twice the number of operations on the data.

Furthermore, as demonstrated by Lazaratos (1993), the coherency of the stacked image may be enhanced if reflections can be identified in the individual gathers. Lazaratos used a velocity model derived from a tomographic inversion of the direct arrival traveltimes to map the reflection arrivals. He found that mapping with this velocity model did not perfectly align reflections from different gathers at a common reflection point and that residual moveout corrections were necessary to maximize the coherency of the stacked image. These residual moveout corrections were enhanced by the ability to identify reflections in the individual mapped gathers (the reflection arrivals had been wavefield separated prior to mapping). Consequently, we evaluate reflection quality in Figure 9 on a single mapped gather rather than after stack, since the coherency of the final stacked cross-well reflection image may be dependent upon the coherency of the reflection arrivals in the individual gathers.

CONCLUSIONS

Cross-well seismic data consist of a complex suite of arrivals that include direct waves, upgoing reflections, downgoing reflections, and multiples. Identification of arrival type can be facilitated by analyzing the data in multiple sorting domains. In this regard, cross-well data are more like surface seismic data than VSP. Direct arrivals and some multiples can be distinguished from primary reflections (both

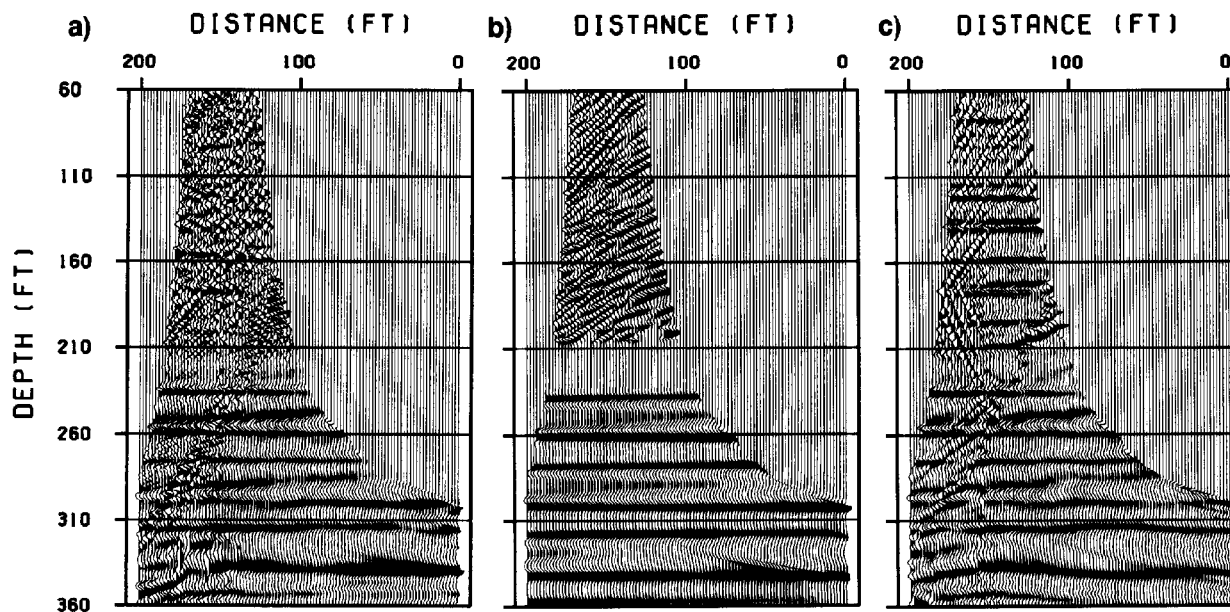


FIG. 9. Imaged downgoing reflections (a) obtained from acoustic synthetic using common-offset wavefield separation (b) modeled with geometric ray tracer (c) obtained from acoustic synthetic using common-source wavefield separation. The data have a 30 ft (9 m) AGC. Note that the common-source wavefield separation retains artifacts above 210 ft (60 m) related to multiples and reflections are generally more broken.

upgoing and downgoing) by analyzing the data in common-offset space. In common offset, the direct arrival has little moveout while the reflections have roughly double the moveout magnitude of reflections in common source or receiver space. With a synthetic example, we show that by performing moveout-based wavefield separation in common offset, primary P reflections can be separated from both the direct arrival and some multiples, thereby improving the prestack image quality.

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